THE FAST ALTERNATIVE CRYOGENIC EXPERIMENT TESTBED

A. Nash[1], P. Shields[2], R. Abbott[3], J. Craig[4] and W. Holmes[1]

[1]Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA

[2]Janis Research Company
Wilmington, MA 01887, USA

[3]Ball Aerospace and Technologies Corporation
Boulder, CO 80306, USA

[4]Swales Aerospace
Pasadena, CA 91107, USA

Abstract

Subsystems for a "proof of concept" cryogenic payload have been developed to demonstrate the ability to accommodate low temperature science investigations within the constraints of the Hitchhiker siderail carrier on the Space Shuttle. These subsystems include: a hybrid solid neon - superfluid helium cryostat, a multi-channel VME architecture Germanium Resistance Thermometer (GRT) readout and heater control servo system, and a multiple thermal isolation stage "probe" for thermal control of helium samples. The analysis and tests of these subsystems have proven the feasibility of a cryogenic Hitchhiker siderail carrier payload.

Keywords

Space Cryogenics, Cryostats, Superfluid helium (He II), Neon, Instrumentation, Temperature sensors,

Introduction

The Fast Alternative Cryogenic Experiment Testbed (FACET) project was a one year proof of concept study to demonstrate, through the design, construction, and test of subsystem prototypes, the feasibility of flying cryogenic payloads aboard the Space Transportation System (STS) (a.k.a. the space shuttle) during the International Space Station (ISS) build era. This paper summarizes the development of the key payload prototype subsystems built and tested. A more detailed description of the cryostat and its development is given elsewhere[1].

This paper will describe: the objectives, requirements and constraints for the payload and its development, the design approach, the as built design, as well as the analyses and tests conducted to verify the feasibility of the objectives.

The start of the build era for the International Space Station (ISS) has resulted in the end of regularly scheduled microgravity science opportunities such as the United States Microgravity Payload (USMP) missions on which the Lambda Point Experiment (LPE) and Confined Helium Experiment (CHeX) flew. In addition, the ISS is not scheduled to be completed enough for the planned Low Temperature Microgravity Physics Facility (LTMPF) to conduct experiments until 2003 at the earliest. This situation not only delays the completion of the backlog of existing low temperature microgravity science experiments, but it also compromises the ability to conduct any incremental tests of scientific or technological concepts in microgravity until after the start of the Space Station era.

To address this gap in manifest opportunities, several approaches were investigated. An earlier flight of the planned LTMPF is dependant not only on timely completion of the ISS, but also relies on an accelerated funding schedule to develop the LTMPF itself. The size and weight of the existing Low Temperature Platform (LTP) cryostat[2] used for LPE and CHeX requires a cross-bay carrier mount which is not in the baseline space shuttle manifest. Furthermore, in the case of an ISS schedule slip, the carriers most likely to be manifested are pressurized modules, such as SPACELAB, which are not compatible with crossbay carriers.

The other option investigated was the possibility of a new facility compatible with one or more carriers in the baseline shuttle manifest. This new facility is called the Fast Alternative Cryogenic Experiment Testbed (FACET).

The FACET project objectives were derived from the ultimate goal of producing a simple, low cost, facility providing frequent flight opportunities before the availability of the Low Temperature Microgravity Physics Facility (LTMPF) for existing flight definition Principal Investigators. The prototype was to demonstrate, within tight schedule and cost constraints, the feasibility of a flight system by the test of ground hardware of which the technical approach could be used to develop low cost flight hardware. It was desired that the flight system should be compatible with multiple reflights, each capable of supporting a different investigation. The key performance requirements are listed in Table 1.

In this development, cost and schedule were the driving constraints, with technical scope and performance secondary.

The science objectives to be accomplished within the FACET facility are related to the manipulation and measurement of the thermodynamic variables associated with processes that occur at liquid helium temperatures in a microgravity environment.

The performance requirements were derived from minimum mission requirements negotiated with the backlogged investigators or their representatives.

A block diagram of the FACET payload is shown in Figure 1. The prototype subsystems that have been developed are labeled in bold type. Items labeled in plain type were simulated using ground support equipment. Items labeled with italicized text were not part of this prototype effort

The functional breakdown of the FACET payload is nearly identical to the Low Temperature Platform (LTP) used for the Lambda Point Experiment (LPE) and the Confined Helium Experiment (CHeX).[3]

The components can be organized into four major subsystems: cryostat assembly, instrument, facility electronics, and instrument electronics.

The cryostat assembly includes the dewar itself, as well as the vent plumbing manifold necessary to alter the vent rates while on orbit. Unlike the LTP, however, the FACET payload does not have a vacuum pump. This is due to mass constraints and the fact that the Hitchhiker Siderail (HH-S) carrier does not have "T0" power during the 65 - 161 hour period between last servicing and launch.

The instrument needs to provide a structure for mounting the experiment specific sensor package. This structure needs to be constructed in such a way as to provide several layers of thermal control. The instrument also needs to provide a way to admit and thermally isolate the helium sample under study.

The facility electronics provide five principal functions. Power is filtered, converted, and distributed within the payload. It provides the communications interface with the Hitchhiker avionics. It processes commands and telemetry. It monitors cryostat housekeeping data. It is also designed to monitor the two principal sources of environmental interference for low temperature microgravity fundamental physics instruments. Therefor it includes a Charged Particle Monitor (CPM) and an accelerometer to measure g-jitter.

The exact functions of the instrument electronics will be somewhat experiment specific. However, all of the backlogged low temperature microgravity science experiments require several channels of commandable thermal control, divided between Germanium Resistance Thermometry (GRT) and High Resolution Thermometry (HRT).

Due to tight development constraints, prototypes of only a few subsystems of the payload could be developed. The technology readiness level of all subsystems within the proposed flight payload was assessed, and those subsystems requiring the most development were the ones chosen for prototype development. All subsystems not demonstrated by the development of prototype hardware can inherit design elements from other flight qualified systems. All interfaces are well understood.

Only a few flight elements are missing from the prototype cryostat. Among these are the burst disks required to meet shuttle safety requirements[4] for cryogenic payloads, and motor driven cryovalves. In both cases, locations and envelopes have been specified in the design for known Commercial Off The Shelf (COTS) items to be installed in a flight article. The motor driven cryovalves are necessary to reduce the heat leak to the helium reservoir, the majority of which in the prototype is due to the radiated heat leak around the actuators for the manual cryovalves. In addition, a flight article would require a phase separator of the type developed for SHOOT[5], which would be fed by Liquid Acquisition Devices (LADs)[6], as well as a "standard" sintered stainless steel porous plug.

Due to the development constraints, it was decided not to include a cryo pump of the type required for previous flight experiments[7] in the prototype instrument. However, the location and envelope has been specified in the design for such an item to be installed in a flight article. The development constraints also precluded any design effort to eliminate heating caused by launch vibrations[8] to levels where an exchange gas would not be necessary in the instrument guard vacuum cavity during launch. The pneumatically operated, normally closed cryovalve used in the prototype has not been qualified for flight use, but a valve with identical function and smaller envelope has been[9].

Within the instrument electronics, due to tight development constraints, the readout for Superconducting Quantum Interference Device (SQUID) sensors was not prototyped. Flight qualified systems[10], however, have been developed, the approach of which should be easily adaptable to our architecture.

The facility electronics requirements for FACET are similar to previously flown low temperature microgravity physics experiments[3], and thus were not prototyped. In fact, Ground Support Equipment (GSE) from those previous flight experiments was used to simulate the facility electronics interface to the instrument electronics and cryostat during testing of those prototype subsystems.

The scenario for integration, test, and operations of the payload is listed in Table 2. System level activities begin with the delivery of the investigator's flight instrument to the Jet Propulsion Laboratory (JPL) and ends after post flight checkout. System integration & test is complete when the experiment specific hardware is installed and working within the flight facility. Environmental test verifies the system's compliance with shuttle requirements associated with the launch and/or space environment. Tests may include; random vibration tests, modal tests, thermal/vacuum tests, and electromagnetic interference (EMI) tests as well as electromagnetic compatibility (EMC) tests. Before the system leaves JPL, all shuttle safety verification requirements (analysis, etc.) must also be completed.

The next level of integration and testing occurs at the Goddard Space Flight Center (GSFC) in Maryland where the flight system is combined with the carrier and tested for EMI/EMC compatibility at the payload level.

The hardware is then shipped to Kennedy Space Center (KSC) in Florida. After a post shipment checkout, the hardware is integrated with the shuttle orbiter in the Orbiter Processing Facility (OPF). From here the orbiter proceeds to the Vehicle Assembly Building (VAB), where among other things, the shuttle is integrated with the Solid Rocket Boosters (SRBs). During this approximately week long period there is no payload access. The shuttle then rolls out from the VAB to the launch pad, where the payload is accessible again. Payload access at the pad can take place from the arrival of the shuttle at the launch pad (approximately 1 month before launch) until 65 hours before nominal liftoff (L-65 hours). Launch windows (depending on mission) can last from less than an hour to no more than 96 hours. Following the LPE/CHeX timeline, within 2 days after launch the system is pumped down & calibrated and ready to begin measurements in microgravity. After the shuttle lands, de-integration of the system from the shuttle and the hitchhiker carrier is followed by any post flight testing and calibration that is required by the individual investigator.

In manner nearly identical to the USMP missions, payload command and telemetry is achieved through Ground Support Equipment (GSE) Workstations at a Payload Operations Control Center (POCC) via the Johnson Space Center (JSC). The Hitchhiker POCC is at GSFC. NASA will provide computer compatible media of the payload data and standard orbit, attitude, and ancillary data for test purposes and for flight acquired data. The flow of payload command and telemetry data is shown in Figure 2.

Methods

Payloads are accommodated in the space shuttle by way of carriers. Each of these carriers brings with it a fixed set of capabilities (mass, volume, telemetry, etc.) which in turn affects their manifesting opportunities. A carrier trade study was conducted for the FACET concept, and it was determined that the carrier whose capabilities most closely matched the capabilities of the current Low Temperature Platform, with the highest probability of manifesting opportunities, with the lowest demand on resources, was the Hitchhiker siderail (HH-S) carrier.

Many aspects of the HH-S carrier increase the probability for manifesting opportunities. Hitchhiker has historically been manifested 4 times a year, and has flown along with a wide range of payload masses. Hitchhiker payloads have flown during: a (5,586 lb.) TDRSS satellite deployment mission, MIR servicing missions, SPACELAB pressurized module missions, as well as the United States Microgravity Payload (USMP) series on which LPE and CHeX flew. The hitchhiker office has an agreement to fly on a "mass available" basis during the station build era. In fact, Hitchhiker Siderail payloads have flown during the mission which deployed the first US module of the ISS, the Unity module, and the first servicing mission. The roughly order of magnitude smaller mass of the hitchhiker when compared to other carriers promises more manifest opportunities.

The Hitchhiker project was established by the NASA Headquarters Office of Space Flight (OSF) to develop and operate carrier systems for low-cost and quick-reaction accommodation of secondary payloads on the Space Shuttle. The FACET payload has been designed as a "rapid response" payload, only requiring 9 months from approval to launch.

However, baselining the Hitchhiker Siderail (HH-S) as the carrier, placed challenging constraints on the design[11]. Among the most driving constraints were that the body of the cryostat needed to fit within an envelope 0.64 X 0.64 X 0.99 m, and mount to the siderail with a total mass (including mounting hardware) of less than 880 kg. Another design constraint is the requirement for the internal cryostat structure to have a lowest natural frequency of 35 Hz or greater. Probably the most design driving constraint is the ability of the cryostat to safely operate unattended for at least 65 hours, but as long as 161 hours (for a 96 hour launch window), before launch. Ultimately, the cryostat was designed[1] so that the helium will be left to boil under atmospheric pressure to provide vapor cooling during the period between last servicing and launch, and be pumped superfluid once on orbit.

The issues driving the instrument electronics design came from the desire to support several investigators over the course of multiple reflights of the facility payload. In order to do this, the system needed to be modular, and provide a method by which individual investigators could develop a high fidelity testbed for development of their own investigation specific circuits should they desire.

For these and other reasons, a VME bus architecture was chosen. Another benefit of using the VME standard bus is the availability of Commercial Off The Shelf (COTS) processors, including radiation hardened versions for flight use.

Another major development in the approach taken is the use of a Digital Signal Processor (DSP) interface between the VME bus and the sensor interface circuits[12]. This approach solved some of the real time interrupt response problems seen in the single processor system used on LPE and CHeX. In addition, this approach provides scalable processing power, including programmable signal processing and control at the board level.

The FACET payload concept consists of several different subsystems, that in combination provide both the experimental environment, as well as the instrument control and readout thereof, to conduct low temperature microgravity investigations. The FACET flight configuration is shown in Figure 3. The flight configuration uses two umbilically attached adjacent Hitchhiker siderail (HH-S) mounting locations; one for the electronics subsystems (facility & instrument), and one for the cryostat subsystem.

The cryostat is a hybrid solid neon - liquid helium with "folded tube" G-10 supports. This hybrid approach was taken in part to provide adequate on-orbit lifetime for instruments with high (conducted) heat loads from the instrumentation wiring. There are two vapor cooled shields, in addition to the shield attached to the neon reservoir. The instrument cavity has an interior diameter of 16.51 cm and a depth of 30.48 cm, exceeding the development requirement. The instrument cavity has a vacuum independent of the cryostat vacuum when sealed with the instrument cold flange (and pumped through an instrument provided instrument guard vacuum vent). Heat transfer from the instrument to the helium is accomplished via conduction through the (annular) reservoir's walls. There exist field joints in all vapor cooled shields at the same axial location as the cold flange joint to aid in integration. The shield closure plates and warm flange (collar) interface are modular to accommodate a wide variety of instrument input/output. A photograph of the cryostat is shown in Figure 4 (a).

The instrument structure is principally a scaled version of the one developed for LPE[13], but without the "flex plate". The multipurpose probe design has three stages of thermal isolation with germanium resistance thermometer (GRT) servo control in addition to a sample stage with high resolution thermometer (HRT) servo control. The multipurpose probe design also has one stage of thermal isolation with GRT servo control shared by all

SQUID sensors. The multipurpose probe design supports 4 SQUID sensors which can be used for any combination of superconducting readout devices (HRTs, pressure sensors, etc.). The miniHRT used on the sample stage of the instrument utilizes a Lanthanum diluted Gadolinium Trichloride ($Gd_{1-X}La_XCl_3$) salt. The thermometer was "self charging" utilizing a permanent magnet for the magnetic field used to bias the paramagnetic salt[14].

The cylindrical volume within the radiation shield for the experiment specific sensor package is approximately 10.9 cm in diameter by 11.1 cm deep, exceeding the development requirement by a factor of two. The multipurpose probe prototype also included a circulator line for precooling the instrument, as well as lines for sample fill and pneumatic (prelaunch) actuation of a normally closed cryovalve. For testing, the probe prototype contained a 50 cc liquid ^4He sample cell. A photograph of the instrument (without sensor package radiation shield) is shown in Figure 4 (b).

The target processor chosen was the DY 4 SVME/DMV-177 with Motorola PowerPC™ 603e RISC CPU running a VxWorks Real Time Operating System (RTOS). The interface to the host workstation was via ethernet. The user interface on the host workstation was implemented in Labview.

Each of the two Germanium Resistance Thermometer (GRT) cards contained: GRT readout electronics, heater drivers, temperature control servos, and the embedded DSP processor; all sufficient to each control two individual GRT based temperature controlled stages (i.e., four channels of control authority reside on two cards). The DSP chosen was the Analog Devices 2181. The interface between the VME bus and the DSP was achieved via a Xilinx 4013E Field Programmable Gate Array (FPGA). The design utilizes AC current excitation and synchronous demodulation techniques to obtain high noise immunity. The GRT reference DAC is 16 bit. The temperature servo is a digital Proportional/Integral (PI) type servo implanted completely in software that resides in the local embedded DSP. Each card contains circuitry for individual calibration of both channels of thermometer and heater signals. The cards themselves contained surface mounted components on multilayer Printed Wiring Boards (PWBs). A photograph of the GRT controller under test is shown in Figure 4 (c)

Results

Measurements of ground performance during simulated on orbit operation agreed well with numerical modelling of the cryostat. The model predicted temperatures and heat flow data inside the prototype cryostat during simulated on orbit operation are shown in Figure 5. The numbers in parenthesis are the actual data from simulated operation. Note that the heat flow into the helium tank is dominated by radiation of 36 mW (from leaks around the cold valve actuators).

The on orbit performance of a flight cryostat has been estimated using the same model, but with a replacement of the manually actuated cryovalves in the internal cryostat manifold and their radiation leaks with commercial off the shelf (COTS), flight qualified, stepper motor driven cryovalves and their smaller conductive heat leak. These valves were first used on SHOOT and have subsequently been successfully used in many other space qualified cryostats. This increases the heat load to the neon to more than double the heat load in the ground simulation, decreasing the neon lifetime to 15 days. This change, however, decreases by an order of magnitude the heat load to the helium. Including the boiloff from the estimated "heater power" necessary to keep the neon solid during the launch hold, and using the efficiency of the conversion from normal to superfluid demonstrated in ground test (57%), we predict that the predicted lifetime, for the proposed flight cryostat, depending on whether the launch is at first (65 hours) or last (161 hours) opportunity, is greater than 15 or 6.5 days (respectively).

A voltage to temperature calibration of the miniHRT subsystem was achieved against a calibrated GRT. The sensitivity of the miniHRT with dc SQUID readout at 2.17 K was ~ 29 $\O_0/\mu K$.

The sample noise power spectrum during HRT control is shown in Figure 6. The noise spectrum was fitted to the following formula which can be derived from the fluctuation dissipation theorem plus a constant for the background from the SQUID noise.

$$\left(T^2\right)_{f+} = \frac{4\tau k_B T^2/C}{\left(1+4\pi^2\tau^2 f^2\right)} + \text{constant} \qquad (1)$$

The integrated noise from this fit is just under 5 nK (4.975 nK) at 2.17 K. This exceeds the development requirement for the prototype. The peaks at 0.4 and 1 Hz correspond to temperature fluctuations on the other stages of the instrument which were not optimally controlled. We note that 1 Hz is the frequency of square wave used in the bridge of the LTC-21 controller that was used to control one of the upper stages of the instrument.

Noise measurements for all GRT channels were made using a 10K resistor to simulate the GRT resistance. A representative scope plots is shown in Figure 7. As shown on the noise plots, the noise density is around 32-34 nv/root-Hz RMS which is a combination of the current source noise, the GRT and Reference resistance Johnson noise, the preamplifier noise, and some contribution from the digital feedthrough at the multiplying DAC.

The FACET temperature measurement resolution specification was 40 μK RMS for a 1 Hz measurement bandwidth, for 10000 ohms/deg-K, and for a 1.0 μA RMS excitation current. The excitation current for these measurements was 0.707 μA RMS, and the figure shown accounts for the difference between the two excitation currents.

Separate tests have been performed to demonstrate the functionality of the heater and servo circuits. Tests with a cryogenic instrument are forthcoming.

Discussion

The agreement between data and numerical simulations from the model used to design the cryostat indicate that the lifetime of the prototype cryostat is limited principally by radiation "leaks" around the manual operators for the cryostat manifold cryovalves. Modelling indicates that a flight cryostat with commercial off the shelf (COTS), flight qualified, stepper motor driven cryovalves would be capable of cooling an instrument for nearly the full duration of even the longest shuttle missions (16 days). The ground tests have proven the ground hold feasibility of the "no pump" hybrid solid neon - liquid helium design for use on the Hitchhiker Siderail (HH-S) carrier.

The sample temperature control in these preliminary measurements was clearly limited by the thermal control in the "upper" stages during this first cool down and operation of the "generic" instrument. Some changes to the heat sinking of the leads in the instrument are under consideration to lessen these effects. The cryovalve performed reliably. High thermal stability instruments for measurements of the thermodynamic properties of liquid helium are clearly feasible within the FACET cryostat.

The operation, in parallel, of all four parallel channels of GRT readout, heater drive, and temperature control servos, has demonstrated the feasibility of the instrument electronics approach to monitor and control the temperature of a multiple GRT based thermal control stage instrument within a FACET payload.

With each subsystem prototype completed within one year from concept to testing, within tight cost constraints ,the FACET prototype development has proven the feasibility a simple, low cost, facility providing frequent flight opportunities for a cryogenic Hitchhiker siderail carrier payload on the Space Shuttle.

Acknowledgments

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration. The work was funded by NASA Microgravity Research Division.

---

[1] Nash A, Shields P, Jirmanus M, and Zhao Z. The Development of the FACET Cryostat, To be presented at the 1999 Cryogenics Engineering Conference.

[2] Petrac D, Israelsson U, and Luchik T. The Lambda Point Experiment: Helium Cryostat, Cryoservicing, Functions and Performance. Advances in Cryogenic Engineering, 38, 1993.

[3]JPL D-11781. Low Temperature Platform Briefing Document. 1994.

[4] NSTS 1700.7B, Safety Policy and Requirements for Payloads Using the Space Transportation System. 1997.

[5] P.J. Shirron, J.L. Zahniser, and M.J. DiPirro, A Liquid/Gas Phase Separator for He-I and He-II, Advances in Cryogenic Engineering, 37, (1992).

[6] P.J. Shirron, M.J. DiPirro and J. Tuttle, Flight Performance of the SHOOT Liquid Acquisition Devices, Cryogenics, 34, (1994).

[7] Lysek M. J., Israelsson U. E., Chui T. C. P., and Larson M. E. Design and Testing of an Improved Cryopump for the Confined Helium Experiment.
Advances in Cryogenic Engineering, 43: 995-1000 1998.

[8] McCammon D, Almy R, Deiker S, Morgenthaler J, Kelley RL, Marshall FJ, Moseley SH, Stahle CK, Szymkowiak AE. A sounding rocket payload for X-ray astronomy employing high-resolution microcalorimeters. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 370: (1) 266-268 FEB 11 1996.

[9] Mills G. Design and Development of a Leak Tight Helium II Valve with Low Thermal Impact. Advances in Cryogenic Engineering, 37: 1425 - 1432 1992.

[10] Lockhart JM, Muhlfelder B, Gutt GM, et al. Optimization of a SQUID system for space. IEEE T APPL SUPERCON 7: (2) 2534-2537 Part 3 JUN 1997.

[11] HHG-730-1503-07, Hitchhiker Customer Accommodations & Requirements Specifications, 1994.

[12] Williamson P.R., Bumala R.W., Lipa J.A. Station Processor and Electronics Control (SPEC): New Techniques for Realtime Data Acquisition and Control of Experiments on the External Facility of the Japanese Experiment Module. Proceedings of the 21st International Symposium on Space Technology and Science. Sonic City, Omiya, Japan, 1998.

[13] Lipa J. A., Chui T. C. P., Nissen J. A., and Swanson D. R. A low temperature system for advanced thermal control. Temperature its measurement and control in Science and Industry Vol. 6; No. 2 : 949-952 1992.

[14]Welander P., Barmatz M., Hahn I. A new small nano-Kelvin resolution thermometer for low temperature experiments. Proceedings of the 16th IEEE Instrument and Measurement Technology Conference, vol.1, 413 (1999).

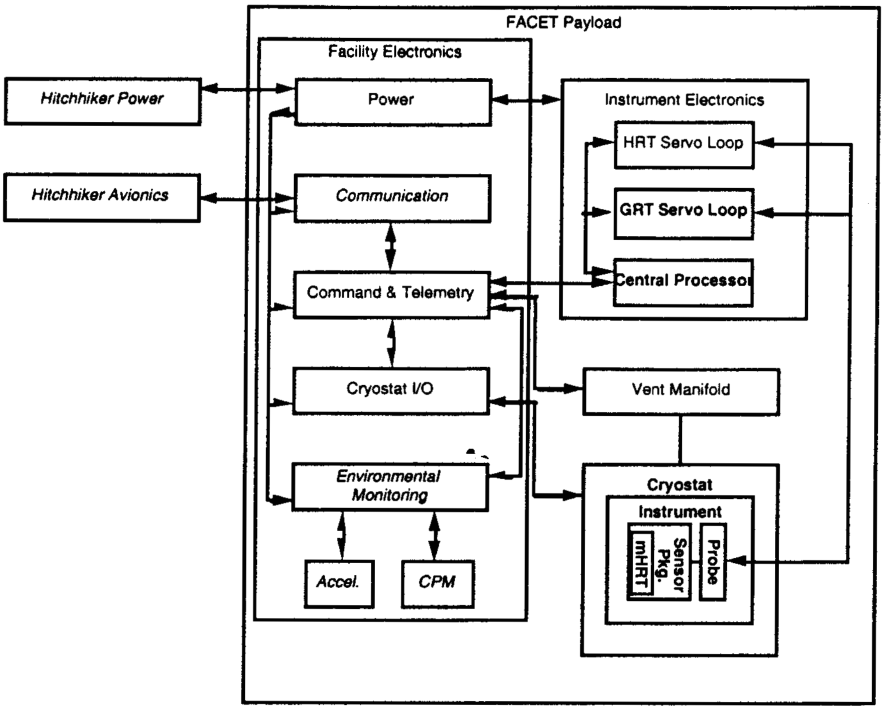


Figure 1 FACET Payload Block Diagram.

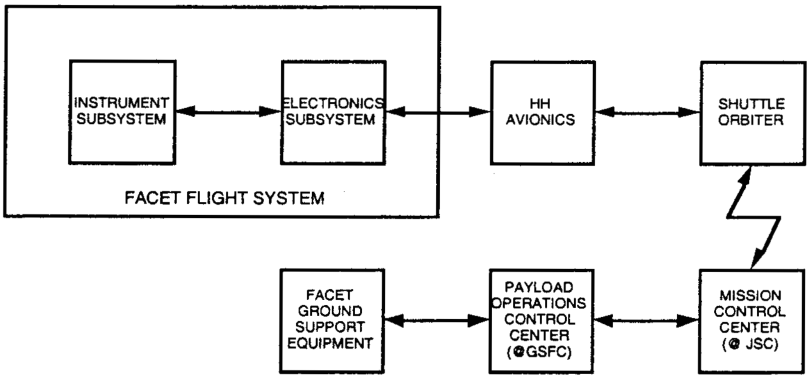


Figure 2 FACET end to end information system

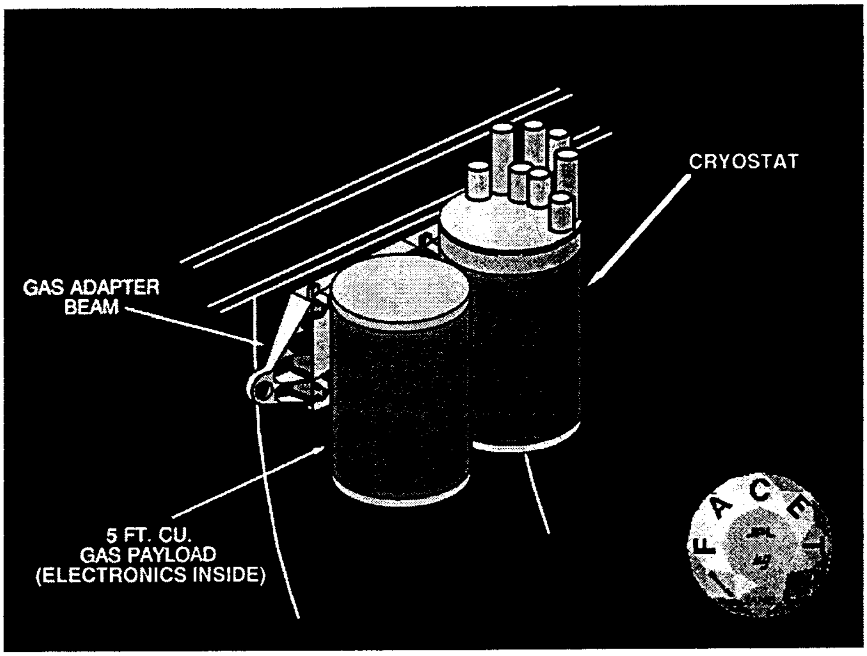
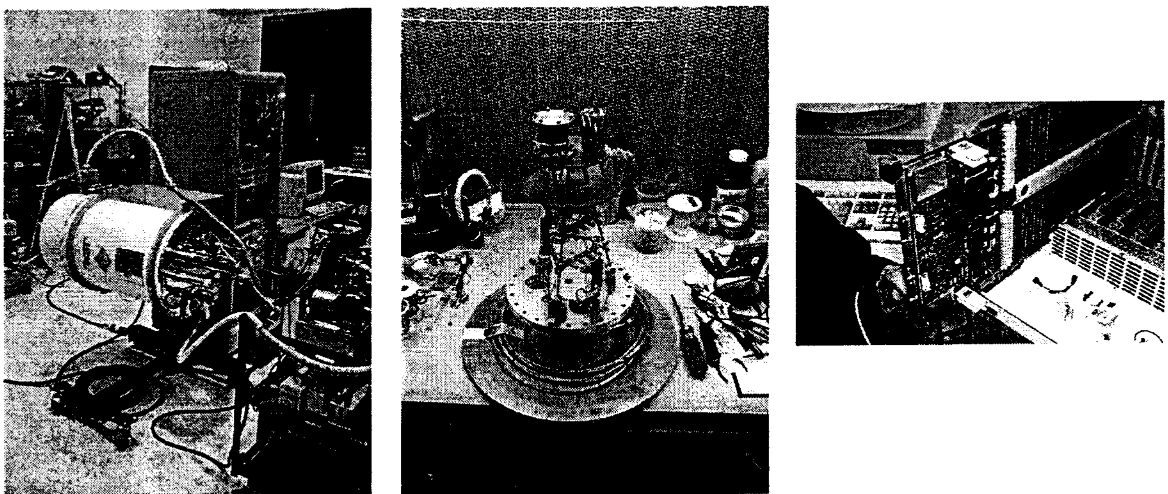


Figure 3 FACET payload design concept



(a) (b) (c)

Figure 4 The prototyped FACET payload elements: cryostat (a), instrument (b), and GRT controller (c)

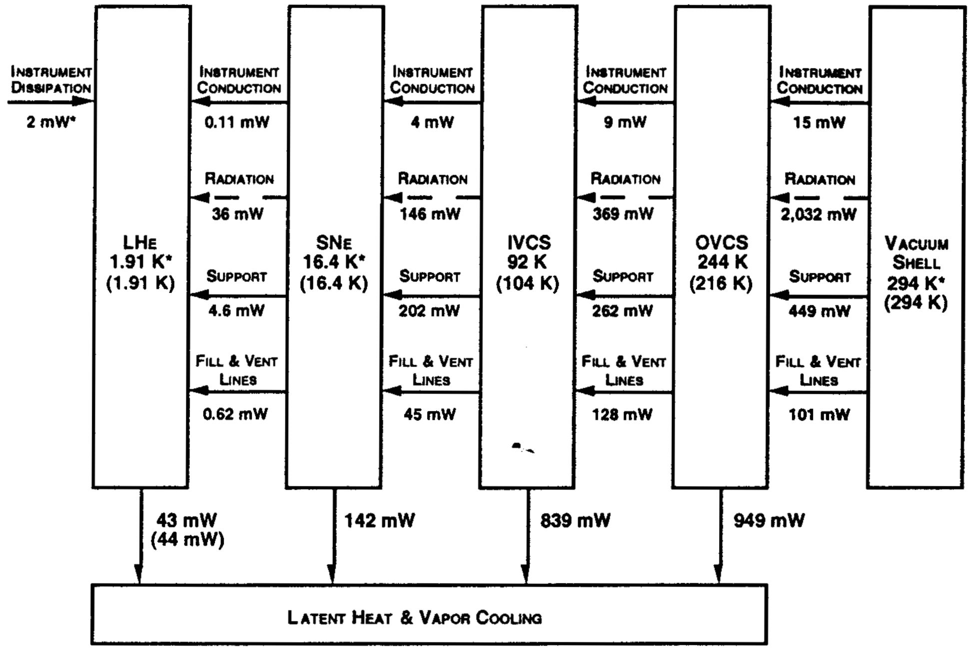


Figure 5 Steady State Model Predictions. Prototype test data are given in parenthesis. Model inputs are marked with an asterisk (*).

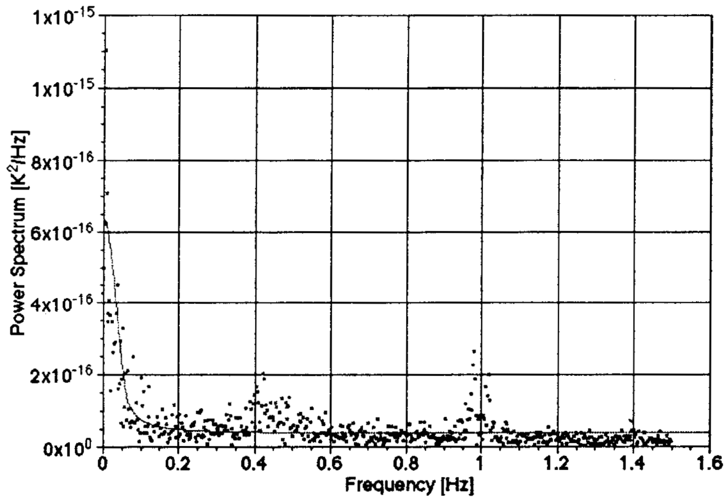


Figure 6 Sample Noise Power Spectrum During mHRT Control

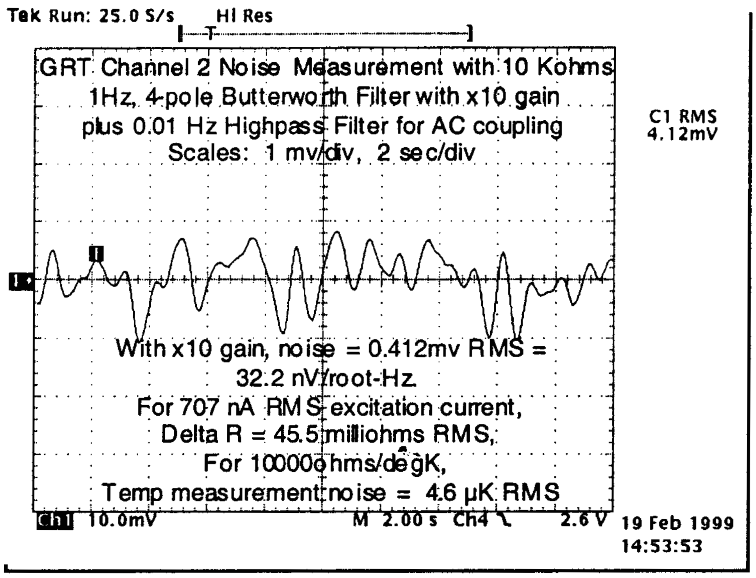


Figure 7 GRT circuit noise measurement

Table 1 Payload Performance Requirements

Subsystem	Parameter	Requirement
Cryostat	On Orbit Lifetime†	$\geq$ 6 days
	Bath Temperature	< 2.17 K
	Instrument Volume	> 4.7 Liters
Electronics	GRT Readout Resolution	$< 40\ \mu K/\sqrt{Hz}$
Instrument	Sensor Package Volume	$\geq$ 0.5 Liter
	Sample Temperature Stability	$<3\ \mu K/\sqrt{Hz}$

† Predicted flight system performance after first launch opportunity

Table 2 Flight System Timeline

Event	Start	End
System Integration & Test	L - 9 months	L - 7 months
Environmental Test (@ JPL)	L - 7 months	L - 4 months
Payload Integration & Test @ GSFC	L - 4 months	L - 3 months
Checkout & Verification @ KSC	L - 3 months	L - 2 months
Orbiter Integration & Test @ KSC	L - 2 months	L - 1 months
Launch Pad Operations	L - 1 months	L - 65 to 161 hrs.
Launch	L - 0	
On Orbit Activation, Equilibration & Calibration	L - 0	L + 2 days
Science Measurements	L + 2 days	L + 6 to 16 days
Post Flight Checkout, De-integration	L + 1 month	L + 3 months